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ADVANCED MODELS FOR AEROELASTIC ANALYSIS OF PROPULSION SYSTEMS

Introduction

In a cooperative project between the University of Toledo and NASA Lewis Research Center, an integrated, multidisciplinary simulation capability for aeroelastic analysis and optimization of advanced propulsion systems is being developed. This research is intended to improve engine development, acquisition and maintenance costs. As a part of this project, development of aeroelastic solvers is underway to integrate the engine component models and the various disciplines such as structures, fluids, controls, etc. One of the proposed simulations is aeroelasticity of blades, cowl and struts in the ultra-high bypass fan. Fans with large ducts and ultra-high bypass ratios are being studied by engine manufacturers. These ducted fans are expected to have significant performance, fuel and noise improvements over existing engines.

The use of these large composite ducts and composite / hollow fan blades makes these configurations susceptible to various aeroelastic phenomena. In addition to classical flutter problems, the possibility of limit cycle flutter due to structural nonlinearities or forced response to the inlet distortions can cause fatigue failure. In the work done under the grant, the methodology and the computer codes for steady and unsteady aeroelastic stability and response analysis of ultra-high bypass fan and other existing designs were developed.

Summary of Work Done

In aero-structures interaction analysis, aerodynamic codes are interfaced with structural dynamics models using steady and unsteady blade deflections, blade loading, etc. An interface program was written to use modal information from COBSTRAN and NASTRAN blade models in aeroelastic analysis with a single rotation ducted fan aerodynamic code (based on level III panel methods). This interface program was written in a general form so that different finite element blade models can be used with minimum changes to the aeroelastic code. The SR3C-X2, F7 and A7 finite element blade models were used to test the interface program and the aeroelastic codes. Using this interface program, an aeroelastic stability analysis was performed. This analysis is intended for analyzing the effect of duct on the aeroelastic stability using ducted and unducted versions of the aerodynamic code. The ducted version of the code can be run with an unducted option or a ducted option.

The aeroelastic stability results from the "unducted version" are identical with the results from the unducted option of the "ducted version" for the single rotation SR3C-X2 model. After completing this validation work, the code was modified to model the main features of E³ engine geometry on a single rotation basis. The E³ fan rotor blades are modeled structurally using platelike finite elements in COBSTRAN and NASTRAN. Initially, the steady state performance cases are being analyzed. The computed values for blade natural frequencies are being compared with the measured values during the wind tunnel tests. Also the computed performance parameters are being compared with the original and corrected design values. Using the steady airloads and centrifugal loads, the blade deformations are being calculated in an iterative manner. This analysis facilitates a comparison between manufactured (cold) shape and operating (hot) shape. This blade deformation calculation also includes the thermal loads provided by a separate analysis.

The aerodynamic codes based on the Euler and Navier-Stokes equations for the ducted fans (ADPAC-APES) were modified and extended to allow blade deformations. Interface programs were written between TIGG3D and structural codes to transfer updated geometry and grid information due to blade deflections. E³ fan rotor blade structural model was verified and part-span shroud treatment was improved. Different levels of sophistication are needed in part-span shroud modeling for accurate hot/cold shape calculation and vibration analysis. See Ref. 1 for more details. Also, datasets were provided to graphics personnel to create a video that shows blade vibrations and motions.

A semi-empirical model was described in Refs. 2 and 6 for predicting unsteady aerodynamic forces on arbitrary airfoils under mildly stalled and unstalled conditions. Aerodynamic forces were modeled using second order ordinary differential equations for lift and moment with airfoil motion as the input. This model was simultaneously integrated with structural dynamics equations to determine flutter characteristics for a two degrees-of-freedom system. Results for a number of cases were presented to demonstrate the suitability of this model to predict flutter. Comparison was made to the flutter characteristics determined by a Navier-Stokes solver and also the classical incompressible potential flow theory.

A numerical eigenvalue problem formulation and a practical calculation procedure for exact eigenvalues and corresponding eigenvectors were developed and applied to a nonlinear, two-dimensional, time-marching full potential solver for cascade aeroelastic stability analysis in Ref. 3. This procedure was based on the Lanczos recursive method and it directly calculated stability information about a nonlinear steady state. It was compared to conventional approaches in the frequency and time domains developed earlier and was found to be 100-10,000 times more computationally efficient. Eigenvalue constellations and the flutter results for flow through a cascade SR5 propfan airfoil were also presented in Ref. 3. Eigenvalue constellations for transonic flow over a NACA 0012 airfoil were presented for both inviscid and viscous cases in Ref. 4.

Another approach was presented in Ref. 5 that allows the time domain full-potential flow solver to be used efficiently to determine aerodynamic data corresponding to small amplitude harmonic blade motions for use in frequency domain flutter calculations. The conventional approach to calculating harmonic aerodynamic data from a time domain analysis is to specify the blade motions to be simple harmonic and to decompose the resulting time-dependent response into Fourier components. This method, in which all the blades are oscillated with a specified frequency and interblade phase angle, is referred to as the Harmonic Oscillation method. The Harmonic Oscillation method does not exploit the linearity of the unsteady flow problem for small amplitudes of motion. In Ref. 5, the principle of superposition was used in the Influence Coefficient method to determine the aerodynamic forces for different values of interblade phase angle by summing the solutions to elemental problems. The elemental problem consists of a cascade with one blade oscillating in harmonic motion while the other blades remain stationary. Next, the Pulse Response method was combined with the Influence Coefficient method to determine the aerodynamic coefficients for harmonic blade motions at different values of frequency and different values of interblade phase angle. This was done by giving one of the blades in the cascade a transient motion or pulse. The resulting transient forces on all the blades were Laplace transformed and combined to determine the aerodynamic forces at a given frequency and interblade phase angle. These methods were validated by comparison with the Harmonic Oscillation method. Finally, the aerodynamic data thus obtained were used for flutter calculations. Flutter calculations were done with a typical section structural model (lumped parameter representation) for each blade. It was shown in Ref. 5 that the combination of the Influence Coefficient method and the Pulse Response method, allows the calculation of the aerodynamic coefficients for several combinations of phase angles and frequencies at approximately the computational cost required for the calculation of a single phase angle and single frequency using the Harmonic Oscillation method.

Aeroelastic stability analyses were performed to insure structural integrity of the U.S. NAVY/Air Force cruise missile counterrotating propfan blade designs. This analysis determined if the counterrotating propfan designs are flutter free at the operating conditions for the wind tunnel test. An aeroelastic analysis code ASTROP2 (Aeroelastic Stability and Response Of Propulsion Systems - 2 Dimensional Analysis), developed at LeRC was modified and then used in this project. ASTROP2 was transformed from a purely research computer code into a design oriented computer code. This included the addition of capabilities such as steady aerodynamic rotor-to-rotor interaction of the counterrotating configuration, and increased automation and accuracy. The aeroelastic analysis method for the counterrotating propfan system used the combination of a finite element structural model and two dimensional steady and unsteady cascade aerodynamic models. Parametric studies were presented to illustrate the effects of rotational speed, Mach number, and number of modes for two counterrotating blade designs in Ref. 7.

Conclusion

This research project was intended to provide an integrated interdisciplinary prediction capability to determine blade geometry under steady loads, flutter motion, stability region and forced response for the advanced engines. The models, that were developed in this research project, have not only advanced gas turbine engine technology, but have also offered some fundamental insights into the fluid-structures interaction problems and modal analysis.

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